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Development of Laser Fabricated Ti-6Al-4V

Henry C. de Groh III
Glenn Research Center, Cleveland, Ohio

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Henry C. de Groh III
Glenn Research Center, Cleveland, Ohio

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

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Henry C. de Groh III
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

LENS (Laser Engineered Net Shaping) depositions with Ti-6Al-4V gas-atomized powder were accomplished at five different temperatures, ranging from 30 to 400 °C, imposed on the base plate. These base plate temperatures were employed in an effort to relieve stresses which develop during the deposition. Warpage of the base plate was monitored. Only a slight decline in warpage was observed as the base plate temperature was increased. Results indicate that substrate temperatures closer to the stress relief minimum of 480 °C would relieve deposition stresses, though process parameters would likely need to be modified to compensate for the higher base plate temperature. The compositions of the as-received powder and the LENS deposited material were chemically analyzed. The oxygen content of the LENS material was 0.154 wt.% which is less than the maximum impurity limit of 0.2% for commercial Ti-6Al-4V alloys, but is over the limit allowed in ELI grade (0.13%). The level of oxygen in the commercial base plate used was only 0.0635%. Tensile specimens were machined from the LENS deposited material and tested in tension at room temperature. The ultimate and yield tensile stresses of the LENS material were about 1200 and 1150 MPa respectively, which is about 20% higher than the strengths of wrought Ti-6Al-4V. The higher strength of the LENS material was due to its fine structure and high oxygen content. The LENS deposits were not fully dense; voids were frequent at the interfaces between deposited layers. These dispersed sheets of voids were parallel to the longitudinal axis of the resulting tensile specimens. Apparently there was sufficient continuous, fully dense material longitudinally to enable the high strengths. Ductility was low in the LENS material. Percent elongation at failure in the LENS material was near 4%, which is less than half of what is usually expected from Ti-6Al-4V. The low ductility was caused by high oxygen levels, and the presence of voids. It is likely that the relatively high scan speeds used in our depositions contributed to the lack of full density in our LENS material.

Introduction

Laser Engineered Net Shaping (LENS) is a direct-metal rapid prototyping process in which powdered metal is propelled toward the focal point of a laser, melted, and deposited. The laser and powder dispensing head move together to build nearly finished parts, layer by layer, according to control software and a CAD drawing of the part being built.[1] Powder that is not deposited is collected and recycled back into the input hopper, thus there is little waste. LENS has been proposed as an economical alternative to some of the more expensive manufacturing techniques, such as chemical milling, for parts such as jet engine after-burner casings. NASA Glenn Research Center has several rapid prototyping facilities, including a LENS machine supplied and serviced by Optomec Design Company. In an effort to build expertise and a foundation of strength for future work in this area, NASA Glenn initiated an effort to examine LENS deposited Ti-6Al-4V and how this alloy and LENS might be applied to the aerospace industry. This report details the results of that investigation, which was truncated when the NASA Aeronautics Program was re-structured.

Titanium is an allotropic element, with the hexagonal close-packed (hcp) alpha phase stable at lower temperatures, and the body-centered cubic beta phase stable at higher temperatures. Ti-6Al-4V is known as an $\alpha + \beta$ alloy because both phases are usually present at room temperatures. The amount and crystallographic form of these phases depend on processing. The initial solid that forms during solidification is the beta phase. As the solid cools, the beta phase decomposes, usually by martensitic transformation. The beta-to-martensite transition is responsible for the acicular (platelike) structure in rapidly cooled titanium alloys, often referred to as a Widmanstatten structure. If Ti-6Al-4V is given a softening mill anneal, globular crystals of beta in a matrix of alpha result with yield and ultimate strengths of about 945 and 1069 MPa respectively.[2] With solution and aging heat treatments a Widmanstatten structure results, consisting of fine acicular alpha, alpha at former beta grain boundaries, and yield and ultimate strengths of 1103 and 1151 MPa respectively.[2,3]

The strength and ductility of titanium alloys are also influenced by the presence of interstitial alloying elements such as oxygen, nitrogen, and carbon, with strength generally increasing, and ductility and fracture toughness generally decreasing with these additions. These low interstitial alloys have particular applications at cryogenic temperatures and in aerospace pressure vessels due to these ductility and toughness improvements; such alloys have been designated ELI for their extra low interstitials. Iron content is also limited in ELI grade Ti-6Al-4V alloys.[2]

Several works have been published detailing LENS equipment, software, process development,[4-8] and resulting structures and properties in Ti alloys.[6,7,9-11] Prior work presented in Ref. 11 has shown the validity of concerns relating to oxygen and nitrogen levels. Low O and N levels are needed to avoid embrittlement in Ti-6Al-4V. Compared to the starting powder, oxygen in the laser deposited material remained the same (0.23 wt.%) and nitrogen increased from 0.032 to 0.048%.[11] These O levels are above the maximum allowed by AMS (Aerospace Materials Specifications) standards for Ti-6Al-4V, and N is very close to the maximum of 0.05 % allowed.[12] This highlights the importance of starting with clean low O and low N powders. The microstructure produced by the 14 kW CO_2 laser appeared to consist of transformed beta in the form of acicular alpha with alpha at former beta grain boundaries. At laser power levels less than about 5 kW, cooling rates are expected to be high enough to result in martensitic alpha prime. Ultimate tensile and yield strengths were 1007 and 876 MPa respectively.[11] Other work used an 18 kW CO_2 laser, which produced deposited layers about 2.9 mm thick, with a structure consisting mostly of Widmanstatten acicular alpha outlined in retained beta, with alpha at former beta grain boundaries.[8]

Noecker has noted the importance of the size and shape of the starting powder, finding that the irregular shape of water-atomized powder can cause inconsistent powder mass flow rates at the nozzle, and voids in the deposited product.[13] Susan et al. found that LENS intralayer porosity was due to porosity in the starting powder.[14] Goodwin et al. found that voids in laser deposited material could be eliminated by increasing laser power, and that Ti-6Al-4V was very susceptible to the formation of columnar grains, with long columnar grains perpendicular to the substrate dominating the microstructure for a wide range of processing parameters.[9]

One of the problems associated with LENS is residual stresses induced in the deposited and substrate materials. These stresses are particularly detrimental when the substrate upon which the material is being deposited is relatively thin, as in the case of a jet engine after-burner casing. Since no material in the literature was found exploring these residual stresses, their mitigation was a goal of this work. The primary objectives of this work were to better establish LENS capabilities at NASA Glenn and investigate residual stresses resulting from the deposition process. However, funding changes ended this work prematurely.

Experimental Procedure

All LENS depositions were done on 1/8 inch (0.3175 cm) thick annealed Ti-6Al-4V plate, in an argon atmosphere using -100, +325 mesh, gas atomized, Ti-6Al-4V powder procured from Affinity International (Hacienda Heights, CA). The as-received chemistry of the powder was analyzed and found to be: 89.5wt.% Ti, 6.4wt.% Al, 3.94wt.% V, 0.14% Fe, 0.016% Cr with 1400 ppm O, 355 ppm N, 175 ppm C, and 32 ppm H. After the manufacture and testing of the tensile specimens, sections were cut from the grip areas and chemically analyzed. A piece of the commercial plate was similarly analyzed for comparison. Chemical analyses for the metals were by ICP-AES (Inductively Coupled Plasma Emission Spectrometry); analysis for O, N, C, and H were performed using LECO equipment similar to what is used in the steel industry, where O and C are detected by infrared sensors, N and H by thermal conductivity.

The measured power output of the CO_2 laser used to do the LENS depositions was set at 450 W. This is a relatively low power laser, resulting in a small melt pool and fast solidification rates. The upward movement of the nozzle at the completion of each layer was 0.508 mm (0.02 in.). Oxygen levels in the deposition chamber were monitored and maintained at between 3 and 8 ppm. The movement rate of the nozzle, known as the scan speed, was 100 cm/min. (scan speed around the outer edges, called the contour, was 89 cm/min.). Powder mass flow rate was 8 g/min. Hatch angle was 0 and 90°, thus one layer was put down “back and forth” (left to right) and the next layer was put down “top to bottom”, 90° to the previous layer.

Tensile tests

Rectangular depositions 2 cm wide by 15 cm long were laid down on the 0.32 cm (1/8 in.) thick plate, rising up from the plate about 1.8 cm, making a solid rectangular beam. A heating system was built to pre-heat the Ti alloy base plate. Temperatures between room temperature and 400 °C were used during deposition (see Table 1). Ti alloy plates were cut to about 20 cm wide by 25 cm long and secured tightly onto the heater plate.

Depositions were made and small beams machined from them and from the beams, tensile specimens were EDM cut (electron discharge machining). Specimen dog-bones were 0.48 cm (3/16 in.) thick, 15.2 cm long (6 in.), 1.9 cm (3/4 in.) wide at the grip ends, with gage dimensions 0.63 cm (1/4 in.) wide by 3.2 cm (1.25 in.) length. Three to four specimens were obtained from each deposited beam. One specimen from each beam was taken such that half of the material was base plate, and half was LENS material; the tensile specimen thus consisted of two layers, one Ti alloy base plate, the other LENS deposited Ti-6Al-4V. These specimens were made in an effort to determine the strength of the bond between the substrate and LENS material. Room temperature tensile tests were performed using an Instron Instru-Met with a cross head movement of 1.57 mm/min (0.062 ipm) following ASTM – E8 tension test specifications. All tensile tests were done in air at room temperature. Between two and four specimens at each condition were tested; the results presented in Table 1 are the averages of these tests. In an effort to quantify the consistency of the measurements, the variation of the data at each condition was determined, where the variation was defined as the average minus the minimum, divided by the average. The variations were then averaged for all temperatures.

Residual Stress

A rudimentary attempt was made to monitor the amount of residual stress imposed by the deposition. The LENS material deposited on the plate contracts as it cools; this contraction caused the 1/8 in. plate to warp. The amount of this warpage was crudely measured as follows. After deposition, the Ti plate, which was initially flat, was placed on a stone table and the gap between the table and bottom edge of the plate measured. The gap at each corner and at the mid-point of each side was measured. In this way the amount the plate lifted up from the table was found; the eight measurements were averaged to give the average warpage in millimeters.

Dynamic Modulus

The dynamic modulus of LENS deposited Ti-6Al-4V was measured following ASTM standard C1259 and procedures similar to those presented previously.[15] Two specimens were tested; each appeared to be fully dense and were about 5 mm wide, 3.9 mm tall, and 51 mm long.

Metallography

After testing, samples were cut from the grip areas of the tensile specimens, mounted in metallographic epoxy, polished and etched with Keller's reagent (190 ml water, 5 ml nitric acid, 3 ml HCl, 1 ml HF).

Results

Tensile Tests

Tensile test results are presented in Table 1, and Figure 1 through Figure 4. The average variation in the yield stress, ultimate stress, modulus and elongation results in Table 1 were +/- 2.9%, 2.8%, 3.0%, and 33% respectively. Figures 1, 2 and 3 are the stress-strain curves for the Ti-6Al-4V base plate, LENS deposited material with a base plate temperature of 300 °C, and LENS specimen, deposited at 300 °C, and then heat treated at 788 °C for 2 hours, respectively. The 0.2% offset yield stress, ultimate stress and modulus of the LENS deposited material compare well with annealed wrought properties; handbook minimums for Ti-6Al-4V yield and ultimate stress are 830 and 900 MPa respectively.[16] However, the elongation of Ti-6Al-4V is typically in the 10 to 20% range; the elongation of the LENS deposited material was consistently and significantly lower than this. In comparable work,[11] Ti-6Al-4V was laser deposited and then heat treated (in vacuum at 788 °C for 2 hours) resulting in yield and ultimate strengths of 876 MPa (127 ksi) and 1007 MPa (146 ksi) respectively, and an elongation of 8.5%. We examined the influence of this anneal on one of our LENS deposited blanks. After heat treatment (vacuum at 788 °C for 2 hours) the tensile specimen was cut from the blank and tested. Resulting tensile properties of this heat treated specimen are given in Table 1; elongation was improved from 3.7% to 5.2% although still below accepted values for Ti-6Al-4V.

Another factor that may be influencing elongation is oxygen content. Table 2 presents the elemental composition of the base plate, our starting powder and resulting LENS deposited material, the analysis of powder and laser deposited material from Reference 11, and the Standard and ELI composition specifications for Ti-6Al-4V from Reference 2. As noted, the O content of the as received powder was 1400 ppm (0.14%). The O content worsened slightly through the LENS process: the O content of the LENS processed grip end was 1540 ppm. The O content of the commercial Ti-6Al-4V plate was 635 ppm. Hydrogen, C, and N contents in the LENS material were 35 ppm, 190 ppm, and 380 ppm respectively. The maximum O generally allowed in Ti-6Al-4V is 2000 ppm.[16] However, ELI (extra low interstitials) grade Ti-6Al-4V requires O content to be no more than 1300 ppm (and Fe allowed at a maximum of 2500 ppm). Low O, N, C and Fe content improve ductility and fracture toughness, but these improvements are very marginal at the concentration levels of Table 2, particularly at room temperature. At room temperature the ductility of standard and ELI grade Ti-6Al-4V are nearly identical. Note that as shown in Table 1, the elongation of regular and low oxygen wrought Ti-6Al-4V are nearly the same. The gains in ductility and fracture toughness for ELI grade titanium are evident mainly near cryogenic temperatures and are better monitored by consideration of reduction in area and notched tensile strength – which are both about 21% higher in ELI material at -195 °C.[2,12] The interstitial content in our LENS material is near ELI and standard specifications, thus interstitial content is not believed to be responsible for the low ductility of our LENS material; nor can these moderate interstitial levels explain the high tensile strength of our LENS material.

Table 1. Base plate temperatures maintained during Ti-6Al-4V deposition, room temperature tensile properties (YS @ 0.2% off-set) of the LENS material, the as received Ti-6Al-4V Base Plate, a single specimen deposited with a plate temperature of 300 °C and heat treated for 2 hours at 788 °C, a reference value for typical annealed wrought material [12,16] and prior laser-based direct-fabricated Ti-6Al-4V material which had been heat treated (788 C for 2 hr.).[11]

Deposition Temperature deg. C	Room Temp. Yield Stress, MPa (ksi)	Room Temp. Ultimate Stress, MPa (ksi)	Modulus, GPa (Mpsi)	% Elongation
30	1143 (165.8)	1200 (174.1)	116.2 (16.85)	3.3
200	1156 (167.6)	1238 (179.5)	116.3 (16.9)	3.9
300	1172 (170.0)	1231 (178.6)	116.5 (16.9)	3.7
360	1155 (167.4)	1208 (175.2)	113.8 (16.5)	3.6
400	1071 (155.3)	1105 (160.3)	113.1 (16.4)	3.2
300 / 788°C for 2hr	1100 (159.3)	1152 (167)	118 (17.1)	5.2
Base Plate	866.1 (125.6)	968.4 (140.4)	113.4 (16.5)	11.8
Wrought Plate [16]	924 (134)	993 (144)	115 (16.5)	14.0
Wrought Plate low O [16]	827 (120)	896 (130)	-	15
Ref. Laser Dep. [11]	876 (127)	1007 (146)	-	8.5

Table 2 Results of chemical analysis measurements, given in units of wt.%, of the base plate, the powder we used, and resulting LENS material, with standard Ti-6Al-4V and ELI and other laser deposited material provided for reference.

	Al	V	O	N	C	Fe
Base Plate	NC	NC	0.064	0.007	0.01	NC
Powder	6.4	3.94	0.14	0.036	0.017	0.14
LENS	NC	NC	0.154	0.038	0.019	NC
Ref. 11 powder	6.01	3.95	0.23	0.032	NC	0.199
Ref. 11 laser deposited	5.83	3.75	0.23	0.048	NC	NC
ELI spec.	6	4	0.13	0.05	0.08	0.25
Standard spec.	6	4	0.2	0.05	0.1	0.3

Generally speaking, alpha-beta titanium alloys are not “aged” in the classical sense, in that their strength does not come from the precipitation of a strong, secondary intermetallic compound. What is “dispersed” is the beta phase among alpha or martensitic alpha prime, with added strength being derived by the number and fineness of alpha-beta phase boundaries.[2] The rapid cooling evident in the LENS material resulted in very fine martensitic structures and the high strengths observed. The slightly higher oxygen also likely contributed to the relatively high strengths of our LENS material. As the substrate was heated, cooling during deposition declined, resulting in a coarser structure, and a decline in strength, as seen in Figure 4. Note that our LENS material was about 20% stronger than the laser deposited material reported in Ref. 11, even though Ref. 11 laser deposited material had higher oxygen. This was due to the high power laser used in Ref. 11, 14,000 watts, which resulted in slower solidification rates and a coarser structure.

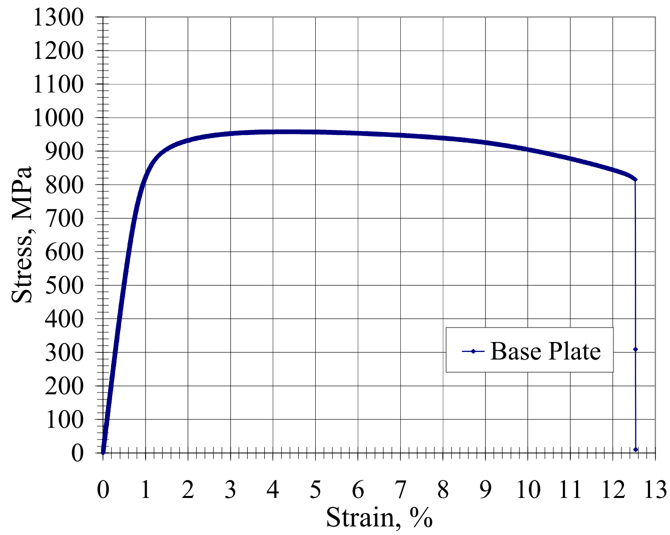

Figure 1. Stress-Strain curve resulting from a tensile test of the Ti-6Al-4V base plate.

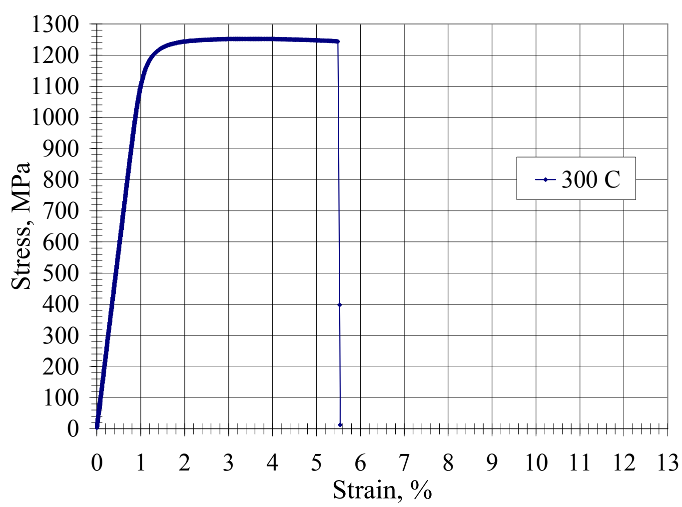

Figure 2. Stress-Strain curve resulting from a room temperature tensile test of LENS deposited Ti-6Al-4V with the base plate maintained at 300 °C during deposition.

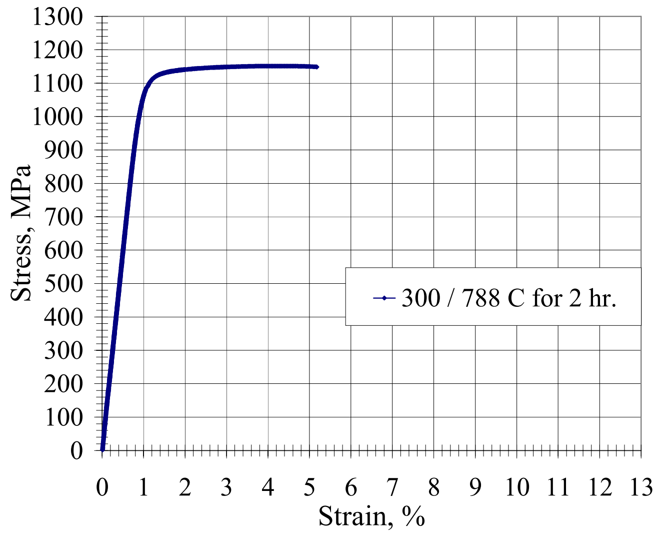

Figure 3. Stress-Strain curve resulting from a room temperature tensile test of LENS deposited Ti-6Al-4V with the base plate maintained at 300 °C, and subsequent heat treatment of 788 °C for 2 hours.

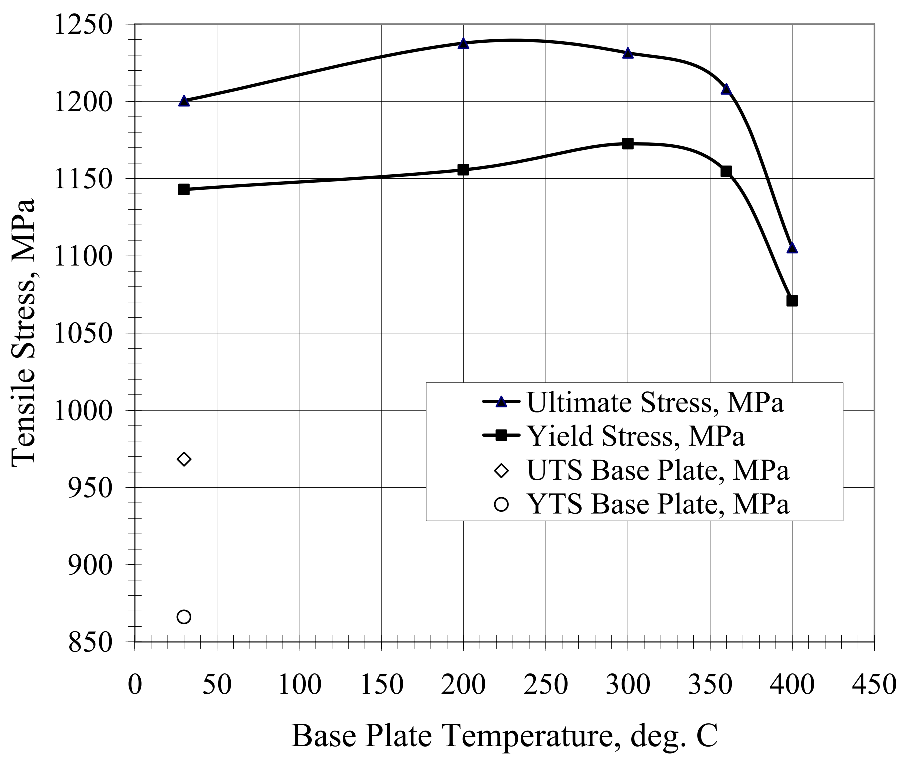

Figure 4. Room temperature tensile results for LENS deposited Ti-6Al-4V at different temperatures imposed on the base plate during deposition; for reference, tensile results for the commercial Ti-6Al-4V, 1/8 inch thick base plate are also shown. Ultimate stress is the peak stress, yield stress is the stress at 0.2% off-set.

Residual Stress

Figure 5 shows the average lift of the edges of the base plate after LENS deposition at different temperatures applied to the base plate. After the deposited material was EDM cut from the plates, the plates sprang back to being flat. A weak trend down can be seen, such that the warpage appears to be decreasing at the higher temperatures. However, it is clear that under these conditions, none of the pre-heat temperatures used eliminated the residual stresses which cause the warpage. Typical stress-relief heat treatments for Ti-6Al-4V alloys are at temperatures between 480 and 650 °C.[2] Thus it is believed that a base plate temperature in this range would eliminate the stresses caused by the LENS deposition. These higher plate pre-heat temperatures would likely lead to the modification of deposition parameters.

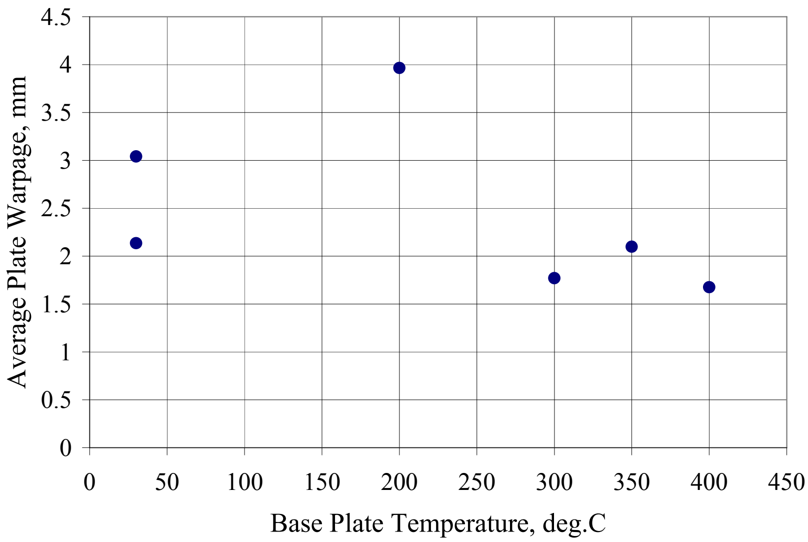

Figure 5. Average lift up of the edges of the base plate, due to the contraction of the LENS deposited material upon it, at different induced base plate temperatures.

Dynamic Modulus

The average dynamic modulus of the LENS deposited material was 117.3 +/-0.5 GPa. The average dynamic modulus of the Ti-6Al-4V base plate was 121 +/-0.5 GPa. These measured values are comparable to literature values. The static modulus of elasticity of Ti-6Al-4V is typically 113.8 GPa [16]; static modulus is generally about 3% lower than the dynamic modulus. This static modulus value is shown as the reference value in Figure 6.

Metallography

Figure 7 shows the structure of the annealed base plate upon which the Ti-6Al-4V was LENS deposited. Titanium has two elemental crystal structures: beta titanium (βTi) which is body-centered cubic, and alpha titanium (αTi) which is close-packed hexagonal. It can be seen on the Ti rich side of the phase diagram [17] that beta Ti is more stable at higher temperatures and alpha Ti is more stable at lower temperatures. Various alloying elements are commonly added to Ti to modify the balance of stability between the alpha and beta phases. Aluminum favors the stability of alpha, and vanadium favors the stability of beta in Ti alloys. Ti-6Al-4V is known as an "alpha-beta" alloy and often has both phases present.[3] The Ti alloy plate we used, shown in Figure 7, has a structure of elongated alpha grains (light phase) in a matrix of transformed beta.

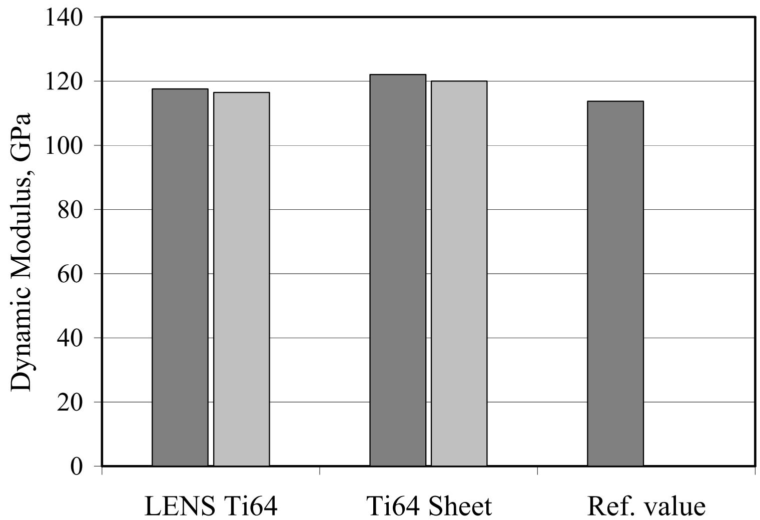

Figure 6. Dynamic modulus of LENS deposited material, commercial Ti-6Al-4V plate, and a Ti-6Al-4V static modulus value for reference [16].

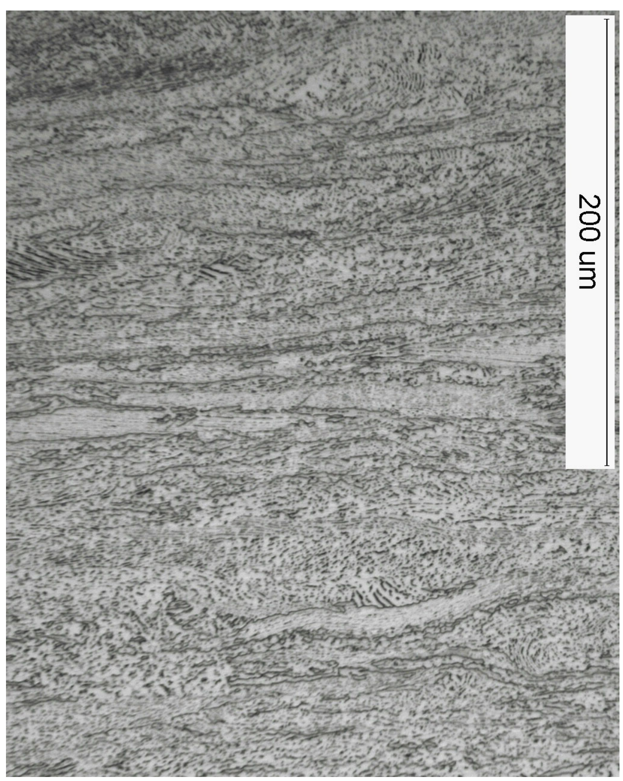

Figure 7. Structure of commercial Ti-6Al-4V base plate; with elongated grains of (αTi) in a matrix of transformed (βTi).

The structure of material deposited onto an unheated base plate is shown in Figures 8 and 9. The interface between the base plate and deposited material is shown in Figure 8. No voids could be seen at this interface. The deposited material is transformed beta with an elongated needle-like structure referred to as acicular alpha. However, at a later time in this room temperature deposition (Fig. 8 and 9), deposition conditions degraded resulting in voids being incorporated between deposition layers; some of these layered voids are shown in Figure 10.

The deposition which maintained the base plate at 400 °C was done many weeks after the room temperature depositions. Process problems resulting in voids remained however, as can be seen in Figure 11, which shows the structure near the interface between the base plate and the LENS material. Large groups of voids are apparent between deposited layers. It is believe that the presence of these voids contributed to the relatively low ductility of the LENS deposited material. The voids do not appear to be caused by the pre-heat treatment, but are believed to be due to less than optimal deposition parameters. As noted in the introduction, others have uncovered several possible causes of porosity in laser deposited material, which include: variations in powder mass flow at the nozzle due to irregularly shaped or poorly flowing powder; mass flow rates set too high; voids in the powder; and laser power levels set too low, causing inadequate melting. Dispersed voids were sometimes limited to a small area, but often a “dotted line” of voids extended across the width of the sample’s cross-section. These dispersed sheets of voids are in the deposition plane, and are thus arranged longitudinally in the test specimens. Apparently, sufficient continuous material was present longitudinally to provide good strength in tension, as evidenced by the good ultimate and yield strengths. At first glance it is tempting to conclude that the porosity seen in the LENS deposited material is caused by insufficient melting due to the laser power set too low. Compared to other work however, the power used (450 W) was rather high. Goodwin et al. obtained voids in their Ti-6Al-4V deposited when low (180 W) power was used, and found that porosity was nearly eliminated as power levels increased to 264 W. Porosity also resulted at low powder feed rates (4 g/min.) and high scan speeds (900 mm/min.). Our scan speed (1000 mm/min.) appears to be rather high, and would likely be a good place to start in future efforts to eliminate the porosity seen in our material.

It can be seen by comparing the structures represented in Figure 9 and 12 that the higher base plate temperature resulted in a coarser structure compared to depositions using a lower base plate pre-heat. The slower cooling, and coarser structure resulting from the pre-heating of the substrate plate are responsible for the drop in strength as pre-heat temperatures rise, as seen in Figure 4. The macro and microstructures of these deposits were very similar to those seen in the literature.[8,9,13]

Figure 8. Micrograph of the transverse cross-section showing the interface between the base plate, at the bottom, and Ti-6Al-4V LENS deposited material on top of the base plate; deposited with no pre-heating of the base plate.

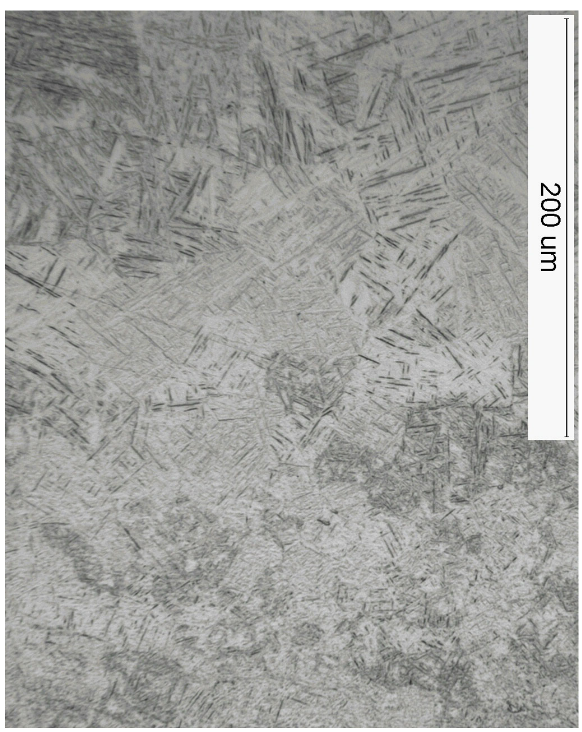

Figure 9. A higher magnification micrograph near the interface between the (room temperature) base plate and LEN deposited material; LENS material appears to be acicular alpha (transformed beta) with small amounts of alpha at former beta grain boundaries.

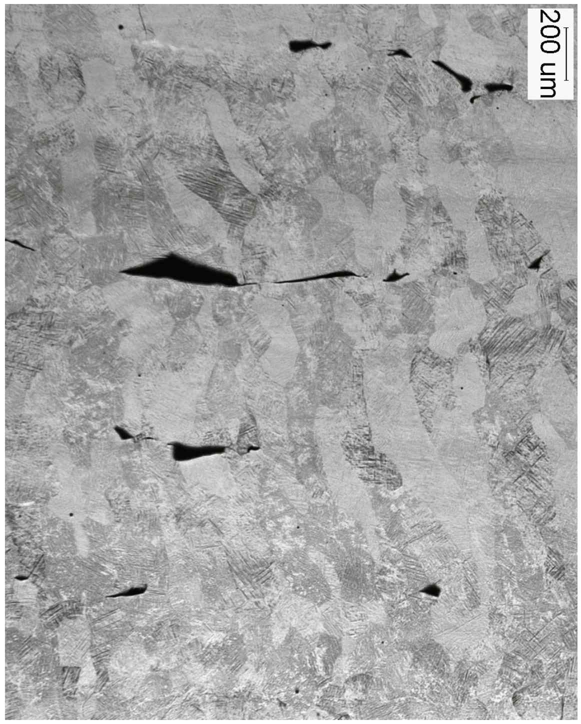

Figure 10. Micrograph of the transverse cross-section, showing voids present in the material deposited with no preheating.

a) b)

Figure 11. Transverse cross-section of the interface area between LENS deposited material and the base plate which was maintained at a temperature of 400 °C during deposition. Voids are present between the plate and the first layer, and between the first and second deposited layers; plate is on the bottom in a) and b).

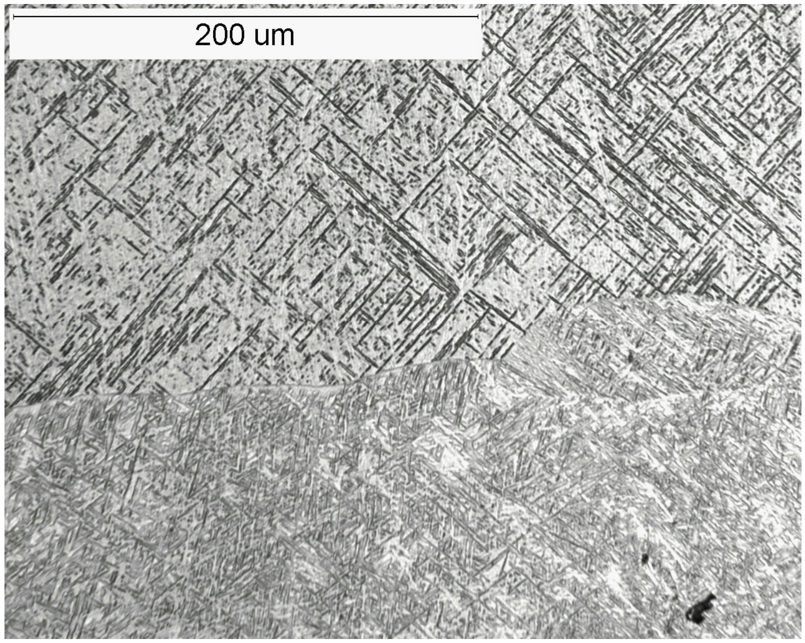

Figure 12. Structure of LENS material using a base plate temperature of 400 °C; acicular alpha (transformed beta) with prior beta grain boundaries.

Conclusions

LENS (Laser Engineered Net Shaping) depositions with Ti-6Al-4V powder were accomplished at five different temperatures, ranging from 30 to 400 °C, imposed on the base plate over a span of several months. Upon metallographic examination, porosity was found between layers of deposited material. Considering the deposition parameters that others have used for Ti-6Al-4V alloys, it was concluded that the relatively high scan speed used in our depositions may have contributed to the porosity. Strength of the LENS material was high due to the benign arrangement of the porosity, the fine martensitic structure, and adequate oxygen content. Only a slight decline in the residual stresses resulting from the deposition were realized at the maximum base plate pre-heat temperature of 400 °C. Other effects of high base plate temperatures were a slight coarsening of the structure, and a slight (9%) decline in strength. It was found that oxygen and nitrogen pick-up during processing were negligible, which is typical of careful LENS processing. Strength levels were consistent with the levels of interstitials and the microstructure of the deposited material. Porosity was present frequently at the interlayer boundaries, but appeared to influence ductility and not tensile strength.

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6. AUTHOR(S)

Henry C. de Groh III

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National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

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13. ABSTRACT ***(Maximum 200 words)***

Laser Engineered Net Shaping (LENS) depositions with Ti-6Al-4V gas-atomized powder were accomplished at five different temperatures, ranging from 30 to 400 °C, imposed on the base plate. These base plate temperatures were employed in an effort to relieve stresses which develop during the deposition. Warpage of the base plate was monitored. Only a slight decline in warpage was observed as the base plate temperature was increased. Results indicate that substrate temperatures closer to the stress relief minimum of 480 °C would relieve deposition stresses, though process parameters would likely need to be modified to compensate for the higher base plate temperature. The compositions of the as-received powder and the LENS deposited material were chemically analyzed. The oxygen content of the LENS material was 0.154 wt.% which is less than the maximum impurity limit of 0.2 percent for commercial Ti-6Al-4V alloys, but is over the limit allowed in ELI grade (0.13 percent). The level of oxygen in the commercial base plate used was only 0.0635 percent. Tensile specimens were machined from the LENS deposited material and tested in tension at room temperature. The ultimate and yield tensile stresses of the LENS material were about 1200 and 1150 MPa respectively, which is about 20 percent higher than the strengths of wrought Ti-6Al-4V. The higher strength of the LENS material was due to its fine structure and high oxygen content. The LENS deposits were not fully dense; voids were frequent at the interfaces between deposited layers. These dispersed sheets of voids were parallel to the longitudinal axis of the resulting tensile specimens. Apparently there was sufficient continuous, fully dense material longitudinally to enable the high strengths. Ductility was low in the LENS material. Percent elongation at failure in the LENS material was near 4 percent, which is less than half of what is usually expected from Ti-6Al-4V. The low ductility was caused by high oxygen levels, and the presence of voids. It is likely that the relatively high scan speeds used in our depositions contributed to the lack of full density in our LENS material.

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